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VARIABILITY OF DEPOSITIONAL SETTING ALONG THE NORTH-WESTERN SICILY CONTINENTAL SHELF (ITALY) DURING LATE QUATERNARY: EFFECTS OF SEA LEVEL CHANGES AND TECTONIC EVOLUTION

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ABSTRACT: The geological, geomorphological and sedimentological features of the north-western Sicily continental shelf are here illustrated with the aim to propose a geological model able to explain the Neogene-Quaternary evolution of the Sicilian continental margin in the context of the central Mediterranean region.
Above the continental shelf and upper slope the sedimentary succession, showing along the different sectors of the margin considerably variable internal geometry and stratigraphic relationships with the underlying units, is interpreted as a IV order depositional sequence (Late Quaternary Depositional Sequence, LQDS) deposited during the last eustatic change (last 125 ky). The lower boundary of the LQDS is represented by a subaerial erosional surface formed during the last eustatic sea level fall ended in the LGM (20-18 ka). This unconformity lies above a seaward dipping Pleistocene succession whose depositional architecture is in turn controlled by Quaternary eustatic sea-level fluctuations.
A dense dataset of morphobathymetric and high resolution seismic data allowed to recognize along the continental shelf to bathyal plain system different types of continental shelf with different stratigraphic and morphostructural settings, associated to both large-scale processes and specific factors related to more local control: a) predominantly rocky shelves, both accompanied by a moderate frontal sedimentary prism and with a structural edge, in the structural highs of the Monti di Palermo offshore and around the main rocky headlands (Capo San Vito, Monte Catalfano); b), depositional shelves, in the Castellammare, Palermo and Termini Imerese gulfs, both with a regular seaward deepening of the substrate and with a substrate uplift at the shelf break.
We confirm that depositional sequences in this margin are the result of the interaction between sea level changes and sedimentation, but demonstrate that the tectonic activity has played a key role, not only in the creation of different types of continental shelves, but also to determine the different characters of each sequence in different areas.
The general tectonic uplift during the Pleistocene, together with the episodic alternation of extensional and compressional events, often with strike-slip component, is responsible for the thickness and facies variation both onland, where residual Pleistocene marine deposits today outcrops, and in the continental shelf, where most of the depositional sequences developed and are now recognized. As well tectonic activity exerted a control on the geomorphological features (e.g. pockmarks and mounds) of the present day coastal areas and shelf-slope system, as well as for the submarine canyons and the mass failure processes.

Keywords: continental shelf, sequence stratigraphy, Northern Sicily continental margin, morphobathymetry, neotectonics

1. INTRODUCTION

The continental shelf is a shallow marine area, less than 200 m deep on average with low inclination (less than 1-2°), surrounding almost all the continental plates. It extends from the external edge of the inshore (submerged beach) until the sudden and significant increase in the inclination of the seabed, which indicates the beginning of the continental slope, characterized by much higher values, up to 10°. In this area of "transition" subaerial and submarine processes interact to determine the geological and environmental evolution. It can also record considerably the effects of anthropogenic pollution linked to navigation, mining and other productive activities along the coast.

The knowledge on continental shelves have increased in recent decades thanks to the investigations on mineral resources or hydrocarbons or features of seabed and substrate on which to lay cables, pipelines and platforms. Even the research aimed to fishing and conservation of marine protected areas have acquired a wealth of morphologic, stratigraphic, sedimentological and structural data.

The characteristic feature of the continental shelf is to be periodically flooded by the sea alternatively with periods of subaerial exposure, so landscape, environment and physical-chemical conditions change here dramatically and frequently, at least at the scale of geological time. According to the most recent reconstructions (Imbrie et al., 1984; Martinson et al., 1987; Williams et al., 1988) exposition and flooding phases have occurred all over the world with periodicity of 150-200 ky during the last million years. The continental shelf is thus a highly dynamic environment where studies on the effects of subaerial and submarine processes are essential for a correct reconstruction of the most recent geological evolution.

In addition to eustatic and global climatic processes, regional factors, as tectonic processes and nature of sedimentary supply, affect the geological evolution of the continental shelf. Sedimentation along the shelves is dominated by sand deposition together with organogenic carbonates and marine fossils-bearing pelites, in different percentages depending on the climatic zones, the prevailing type of coastline (high or low) and the presence or absence of large river mouths, as well as the distance from coast and the water depth. The activity of benthic organisms and of various types of traction currents (waves, tides, coastal currents, etc.) characterizes the sediments that

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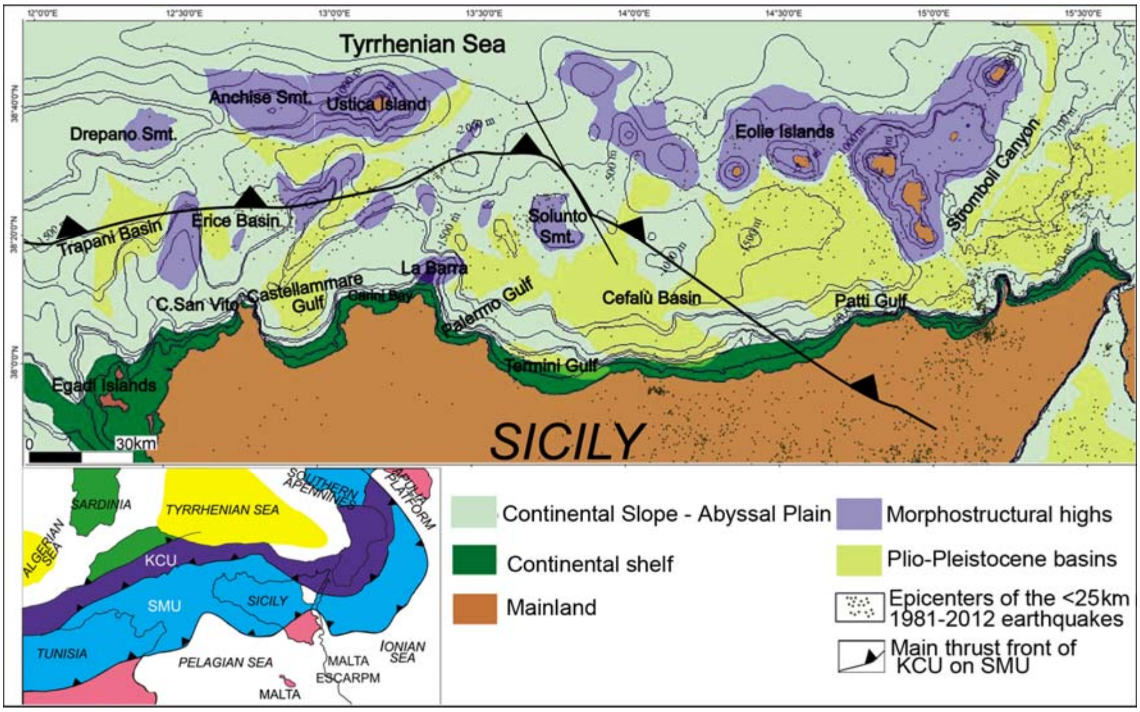

Fig. 1 - Physiography of the northern Sicily continental margin, with location of earthquake epicentres in northern Sicily mainland and offshore. Isobath interval: 0-200 m each 50 m; from 500 upward each 500 m. In the bottom-left corner: simplified tectonic map of the central Mediterranean region.

accumulate in shallow marine environments. Even the presence of special biocenosis (marine phanerogams grasslands, platform coralligenous, etc.), if sufficiently wide, may be relevant.

Northern Sicily continental shelf is a part of the continental margin that links the Sicily chain to the Tyrrhenian back-arc basin (Fig. 1), so it's a key area to understand the processes that occurred in this part of the central Mediterranean, built up mainly during the Neogene-Quaternary.

The scientific interest, connected with the high and variable seismicity of the area, the neotectonic activity, the high and variable uplift/subsidence rate, the occurrence of depositional sequence generated by the interaction between relative sea level changes and sediment supply, and the economic interest, due to the occurrence of bio- and geo-resources, are at the base of the large availability of geological data.

This work describes the geomorphological, stratigraphic and sedimentological features in selected areas of the north-western Sicily continental shelf, summarizing the common features associated with large-scale processes and highlighting the specific factors related to more local control, with the aim to propose a geological model able to explain the evolution of this physiographic units in the context of the central Mediterranean region.

2. GEOLOGICAL BACKGROUND

The northern Sicily continental margin (Fig. 1) is located in the southern Tyrrhenian Sea, from the north Sicily coastal belt to the Marsili Abyssal Plain, in the transitional area between the Sicilian-Maghrebian chain to the south and the Tyrrhenian Basin to the north (Nicolich, 1985; Scarascia et al., 1994).

This continental margin is composed of: (1) a narrow (<8 km) and steep (up to 2.5°) continental shelf, with the edge between -95 m and -140 m. Around 40 m water depth the external sector of the shelf, mainly characterized by hemipelagic sedimentation, is separated by an internal sector with higher hydrodynamics where mainly terrigenous and locally biogenic sedimentation prevails; (2) a very steep (7-8°) upper continental slope ranging in depth from 150 to 1000 m; (3) a flat intra-slope basin plain at a depth of 1500 m; (4) a lower continental slope that is wider and gentler than the upper slope, and (5) a bathyal plain from a depth of 3000 m.

The wave regime (Gulf of Palermo and Termini) is characterized by NW, NE and E directions (Astraldi et al, 2002). The storm waves reach usually 3-4 m in height, have a period of 6 s and an annual frequency of 3% (Istituto Idrografico della Marina, 1982). The tidal excursion indicate a microtidal regime with a tide height varying between 0.37 and 0.60 m a.s.l. The water salinity has no considerable variation between summer and winter, remaining between 37.6‰ and 38.2‰ (Demirov & Pinardi, 2002).

Along the shelf and the upper slope, the Quaternary deposits consist of seawards dipping clastic and terrigenous deposits coming from the northern Sicily (Pepe et al., 2003; Agate et al., 2005), whereas in the basinal areas hemipelagic sediments are locally intercalated with volcanoclastic sediments (Baghi et al., 1980).

In the continental shelf, the Pleistocene deposits are truncated by an erosional surface formed during the last glacio-eustatic oscillation. Local uplift caused the

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systematic non-preservation of portions of the oldest sequences (Pepe et al., 2003). Prograding sedimentary wedges of coastal deposits formed during the Last Glacial Maximum (LGM, about 18 ka) are present along the shelf margin. The prograding wedges are absent where the heads of the canyons or failure scars have indented the outer shelf (Lo Iacono et al., 2011). Integrated high resolution study based both on seismic reflection data and on micropaleontological-sedimentological analisys of a core collected in the outer shelf of the Gulf of Termini, allowed the recognition of two drastic sea-level falls during the Last Glacial Maximum and the Younger Dryas, and provided the different position of sea level during the last 41 ky.

The Northern Sicily continental margin originated as a consequence of a complex interaction of compressional events, crustal thinning and strike-slip faulting. Following the early-middle Miocene deformation and thrusting of the Kabilian-Calabrian units and the most internal units of the Sicilian-Maghrebian chain (Catalano et al., 1985; Pepe et al., 2005), the opening of the Tyrrhenian Sea led to the subsidence of the northern Sicilian margin since the Late Tortonian (Baghi et al., 1980; Fabbri et al., 1981). Late Miocene -early Pliocene north-dipping high-angle reverse faults, involving mainly deep seated, carbonate platform units, produced structural highs (Avellone et al., 2010), among which those seaward bounding the intraslope basins (Pepe et al., 2003), termed peri-Tyrrhenian basins by Selli (1970), filled with Late Neogene to Quaternary evaporitic, hemipelagic, siliciclastic and volcaniclastic deposits, up to 1200 m thick (Baghi et al., 1980). Later, normal faults partly dissected the back- and forelimb of the structural high. Middle-upper Pliocene reflectors clearly diverge towards the normal fault bordering the basin, thereby demonstrating syn-extensional deposition (Pepe et al., 2003). E-W- to NE-SW-trending normal faults exerted during the Pleistocene a control on the morphology of the present day shelf and coastal areas.

As a consequence two types of basins formed in the North Sicily continental margin (Pepe et al., 2005): (1) minor intra-slope basins (e.g. Palermo and Termini basins) whose origin is related to the (?) late Miocene - early Pliocene shortening and thrusting of the Sicilian-Maghrebian Chain, and (2) major extensional basins (e.g. Cefalù Basin) whose origin is connected to the continental rifting which affected the internal side of the margin during the middle (?) -late Pliocene, as demonstrated by synextensional deposition.

The tectonic activity of the northern Sicily continental margin is outlined by a large upper plate seismicity (Fig. 1), producing a seismogenic region characterized by compressional focal mechanisms to the west, while in the eastern sector extensional and strike-slip mechanisms prevail. Shallow (<25 km) seismic events of low to moderate magnitude (max Md 5.6 on September 2002) occur along an E-W trending belt located northward. The focal mechanisms related to the main seismic shocks are in agreement with a dominant NE-SW fault trend coupled with a NW-SE compressive offset direction (Agate et al., 2000; Giunta et al., 2009).

The highest uplift rates during the last 125 ky in northern Sicily (Ferranti et al., 2010) were found on the inner margin-terraces in the eastern coast (0.8-1.63 mm/y), whilst the Holocene rates are between 20% and 70% higher than those calculated for the Tyrrhenian terraces. The vertical tectonic rates show a decrease from E to W. In the Tindari promontory the rate of MIS 5.5 is 0.67 mm/y (Bonfiglio et al., 2010). The Holocene rate is higher, as suggested by Bottari et al., (2009) from the presence of a Holocene tidal notch at 4 m a.s.l.. West of the headland of Tindari, Holocene markers showing increasing rate are not found, presumably due to the coseismic activity of main structural features active during the Pleistocene in northern Sicily: the KabilianeCalabrian Thrust Front (west of Acquedolci) and the Vulcano-Tindari Fault (east of Patti) (Sulli et al., 2012). Further on, both coastal geomorphological and marine geology data between Acquedolci and Capo d'Orlando demonstrate that while the mainland sector is uplifted, with the same rates both during MIS 5.5 (0.34 mm/y) and the Holocene (0.36 mm/y), contemporaneously the offshore area is subsiding, suggesting the existence of fault systems parallel to the coastline, separating the inner from outer sector of the continental shelf, causing different vertical movements (subsidence vs. uplift) (Sulli et al., 2012). Westwards, near Cefalù, some fossil-bearing deposits, dated to MIS 5, at relatively low altitude (29 m, Antonioli et al., 2006) indicated vertical movement rates lower than 0.2 mm/y. Westward, between Palermo and the Egadi islands, many MIS 5.5 markers show a substantial stability, except for small and local vertical movements (Gulf of Castellammare, Mauz et al., 1997 and Castelluzzo Plain), due to the action of transcurrent faults where uplift rates reach 0.1 mm/y (Antonioli et al., 2006).

3. MATERIALS AND METHODS

The morphological features of the area were studied by MultiBeam Echo Sounder (MBES) data, acquired in different oceanographic cruises, by using both the Reson SeaBat 8111, generating 105 beams at a frequency of 100 kHz with depth range of 35-800 m, and the Reson SeaBat 8160, which generates 126 beams with depth range of 30-3,000 m. Bathymetric data were acquired and stored using the PDS2000 acquisition software. Sound velocity profiles were collected with the Navitronic Systems AS-SVP-25. Post-processing of Multi Beam data was accomplished with the PDS-2000 system and included the graphic removal of erroneous beams, noise filtering, processing of navigation data and correction for sound velocity. Gridding of the filtered soundings was carried out to obtain the final DEM (Fig. 2), which provided high resolution 3D views of the seafloor, shaded relief maps, slope maps and bathymetric cross sections.

Various sets of CHIRP and multi- and single-channel seismic profiles provided high resolution to high penetration data of the sedimentary succession. High resolution seismic profiles were mainly acquired employing a multi-tip sparker array, with a base frequency of around 600 Hz, fired each 12.5 m. Data were received with a single-channel streamer with an active section of 2.8 m, containing seven high-resolution hydrophones recorded for 3.0 s two way time (t.w.t.) at a 10 kHz (0.1 ms) sampling rate. Data processing was performed using the following mathematical operators: traces mixing, time variant filters, automatic gain control, time variant gain and spherical divergence correction. The resulting signal penetration exceeded 400 ms (t.w.t.) and the vertical resolution reached 2.5 m at the seafloor. Medium to high penetration seismic data were acquired by using both high power sparker source coupled with single-channel streamer and airgun coupled

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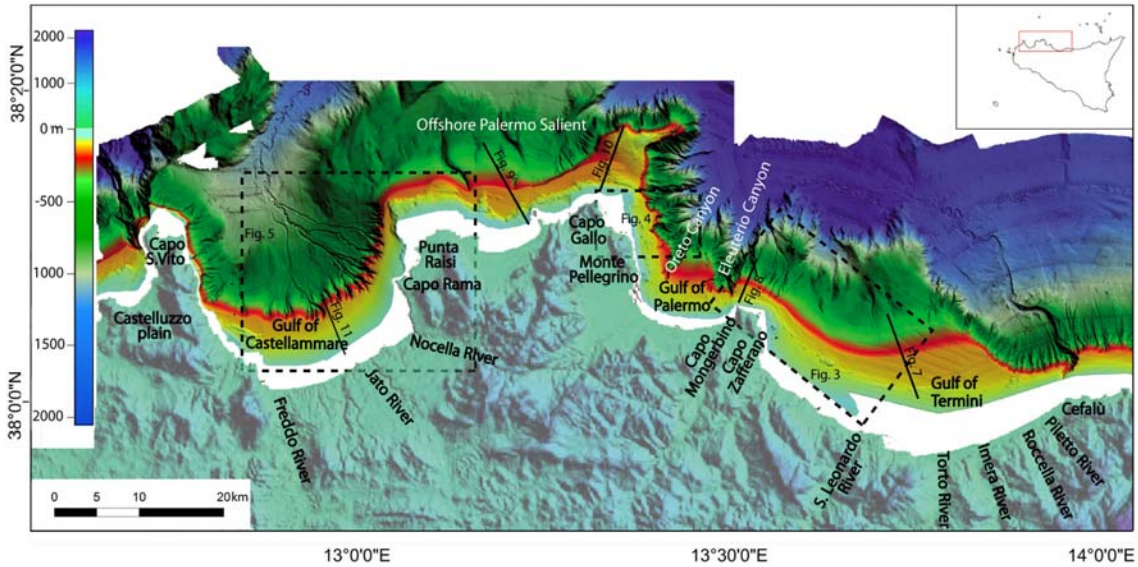

Fig. 2 – 3D shaded relief elevation model of the north-western Sicily mainland and offshore areas. The model shows the main morphostructures and geomorphologic features of the continental shelf to slope region. Intraslope Basin (e.g. Gulf of Castellammare and Gulf of Palermo) are bounded by structural highs of bed rock. The upper slope is scoured by a number of submarine canyons and gullies. According to the elevation scale, the continuous red belt follows the continental shelf edge. The map also shows some of the main toponyms used in this paper. The location of the figures illustrated in the paper is also shown.

multi-channel streamer. The penetration ranges from 1 to 6 s (t.w.t.), with vertical resolution between 10 and 80 m.

The seismic lines were interpreted using seismic facies analysis, which allowed depositional units, characterized by different seismic attributes, to be distinguished. The interpreted seismic lines were depth converted adopting average velocities derived from lithostratigraphy and sonic log data collected in the southern and western Sicilian offshore.

4. GEOMORPHOLOGICAL FEATURES OF THE NORTHERN SICILY CONTINENTAL MARGIN

In order to explain the geomorphological and seismostratigraphic features of the North Sicily continental shelf we individuate some main sectors (Fig. 2), from E to W Gulf of Termini, Gulf of Palermo, Offshore Palermo Salient, Gulf of Castellammare.

4.1. Gulf of Termini

In the Gulf of Termini, average gradient of shelf increases sideways, up to 2.7° offshore Capo Zafferano, with a shelf width ranging from 1.5 km to 8 km (Fig. 2). The seabed appears rather even with the exception of narrow coastal sectors where the substrate outcrops.

The inner shelf is regular and steep due to the depositional slope of the Holocene coastal sedimentary wedge, while the outer shelf is less steep because the Holocene sediments drape a sub-horizontal seabed. The prograding coastal depositional system in the inner shelf developed during the Holocene as consequence of the subaqueous delta coalescence of small rivers that flow to the coast (San Leonardo, Torto, Imera, Roccella and Piletto rivers). An abrupt seaward increase of the sea bottom slope emphasizes the transition from the delta front (slope < 0.5°) to the prodelta (slope of 1°-2°). In some areas, this submarine wedge is extended almost to the shelf edge.

Moving far from the entry points of the sedimentary supply, towards the sides of the gulf, the inner shelf shows a rougher morphology of the sea bed characterized by break-in-slope, paleo-cliff and wave-cut terraces partly buried beneath the thin Holocene sedimentary sheet and the *Cymodocea nodosa* meadow, as offshore Termini Imerese, westward of the San Leonardo River mouth. In the western sector of the gulf, the continental shelf is punctuated by small irregular, isolated relieves partly draped by Holocene sediments.

The shelf break is located at depth between 90 and 145 m. Prograding pattern and straight trend are predominant, but at places a scalloped shelf break is due to canyon headscars (Fig. 3). The upper slope is steeper in the western sector, where a number of submarine canyons develop with parallel thalweg, orthogonal to the isobaths.

4.2. Gulf of Palermo

In the Gulf of Palermo the shelf edge lies at depth of 120-150 m, and 2.3 to 7.5 km far from the coastline (Fig. 2). As consequence, the average continental shelf steepness ranges between 3° in the central sector up to 8° offshore Monte Pellegrino. Different features can be distinguished in the western sector, where the shelf is narrow and steep, and isolated and scattered rocky relieves make the seabed rough, and in the southern sector, less steep and showing a regular morphology without pronounced relieves. Offshore Monte Pellegrino promontory, at depth of 89-92 m, 60-70 m and 35-40 m, three main concave breaks in slopes with wave-cut platforms at base document subsequent sea level still-stands during the last transgression (16-5.5 ka; Fleming et al., 1998). Small, isolated relieves occur in the outer shelf, with the top at depth of 75-90 m, as well as in the southern sector, where the smooth seabed is moved only by a few isolated mound. In the transition zone between the Palermo and the Termini gulfs, a sharp

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concave break in slope, several kilometers long, faces the Capo Mongerbino-Capo Zafferano promontory at water depth of 80-100 m.

The shelf break is as prograding and straight as erosive and very scalloped near the canyon headscars that are extensive along the western sector (Fig. 4). Between the Oreto and the Eleuterio river mouths, no evident shelf break is present: here the margin trends straight but it does not prograde.

4.3. Offshore Palermo Salient

The submerged extension of the Monti di Palermo structural salient, between the Palermo and Castellammare Gulfs, displays a more extensive “structural-erosive” platform, with rougher morphology, mainly in the inner shelf (Fig. 2). The continental shelf, 5 to 8 km wide, is separated, at depth of 60-70 m, by a convex break-in-slope, in inner and outer shelf. In the inner shelf a number of breaks-in-slopes linked to submerged paleo-cliff have been detected at -8 m, -15 m, -35 m, -53 m. In the outer shelf two sectors are separated by a prominent concave break-in-slope 110-120 m deep. Landward of this boundary the sea floor is characterized by rills, isolated relieves and a few concave breaks-in-slopes, interpreted (Lucido, 1992) as paleo-shorelines. Elongated morphological relieves, parallel to the isobaths, and interspaced by narrow depressions have their tops at -75 m, -85 m, -95 m and -105 m. On the base of carbonate cements, recovered from the feature at -75 m (Lucido, 1992), these relievies have been interpreted as beach rocks, recording subsequent sea level still stands during the Holocene transgression. Seaward of the 110 -120 m deep break-in-slope, the shelf margin is characterized by a sub-horizontal surface sloping at about 0.5°, up to 4 km wide. In this sector the seabed is represented by a paleo-wave-cut terrace draped by a thin wedge of Holocene sediments, tapering towards the shelf edge.

The shelf break, about 140-150 m deep, shows mostly prograding geometry, except offshore Capo Gallo and Punta Raisi and in the canyon headscars, here less extensive than in the adjacent gulfs (Fig. 2).

4.4. Gulf of Castellammare

The Gulf of Castellammare is the largest coastal embayment in north-western Sicily, bounded to the East by the Palermo Mountains and to the West by the San Vito Lo Capo peninsula (Fig. 1). Here, a sedimentary basin, more than 1000 m deep, trends in a general north-south direction across the upper slope.

The continental slope deepens to 1000 m, with gradient of 4-9°, and is incised by numerous gullies and major canyons (Fig. 2). Slumping, scours and small turbiditic fans are located at depths from 200 to 800 m, confirming the occurrence of gravity-driven slope instability (Agate et al., 2005).

The coastal belt includes several rocky cliffs along the promontories bordering the Gulf of Castellammare (Capo San Vito and Capo Rama), while a long beach, up to several tens of meters wide, extends in the central sector.

The continental shelf is wave-dominated, with a mean tidal range of about 21 cm (Istituto Idrografico della Marina, 1982). The predominant wave direction is from northwest, while the southwest and southeast are less frequent. Storm waves occur in winter to spring (November to May) and vary in approach direction from northwest to northeast.

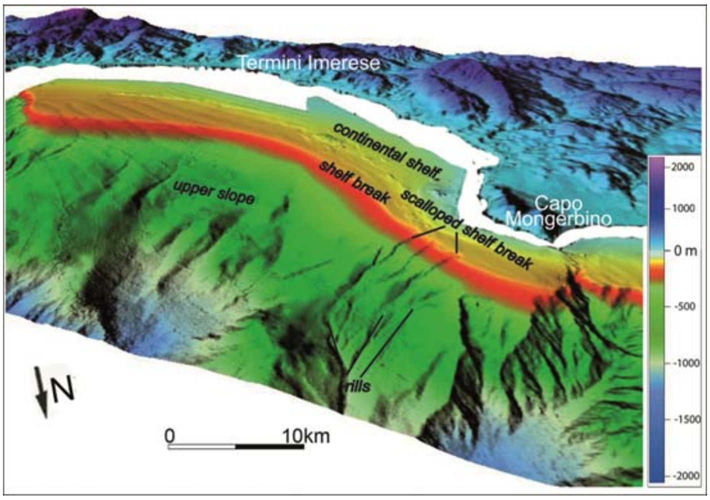

Fig. 2 - 3D shaded relief elevation model of the north-western Sicily mainland and offshore areas. The model shows the main morphostructures and geomorphologic features of the continental shelf to slope region. Intraslope Basin (e.g. Gulf of Castellammare and Gulf of Palermo) are bounded by structural highs of bed rock. The upper slope is scoured by a number of submarine canyons and gullies. According to the elevation scale, the continuous red belt follows the continental shelf edge. The map also shows some of the main toponyms used in this paper. The location of the figures illustrated in the paper is also shown.

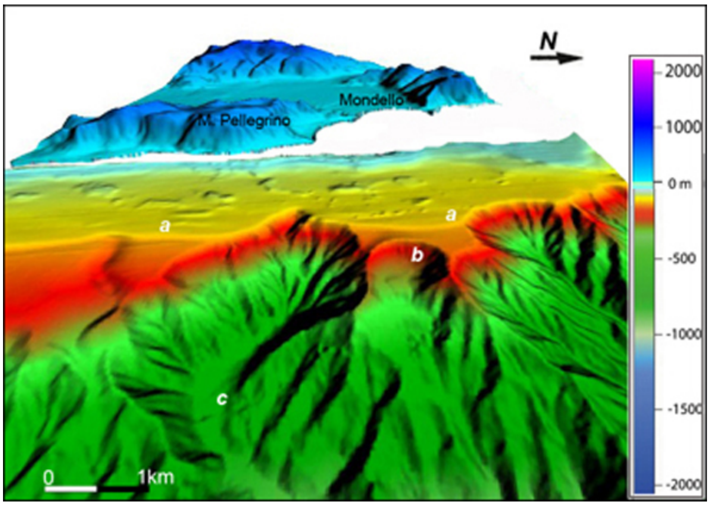

Fig. 4 - Extensive slope failures carve the upper slope sea floor in the western sector of the Gulf of Palermo. Here, small and large canyon heads breach the shelf edge that assumes a very scalloped pattern. a) shelf break; b) submarine slide headscar; c) canyon thalweg (3D shaded relief model, view from East).

The continental shelf is 8 km width on the central part and in the eastern side of the gulf, but it is very narrow or absent along the rocky cliffs of the San Vito Lo Capo peninsula.

The inner shelf, with gradient of 0.7°-1.0°, encompasses 0-50 m, while the outer shelf has a slope of 0.9°-1.2°. The central-western sector of the inner shelf is characterized by convex and concave breaks-in-slope bounding wave-cut terraces and paleo-cliffs; the seabed is punctuated by rocky outcrops and small biohermes.

The Holocene coastal wedge is thicker in the central-eastern sector where the sea bed is rather even and displays an up to 2° gradient in the inner shelf; the bathymetric gradient decreases seawards. The present day shelf margin morphology arises from a former wave-cut terrace mostly buried beneath a thin sheet of Holocene sediments.

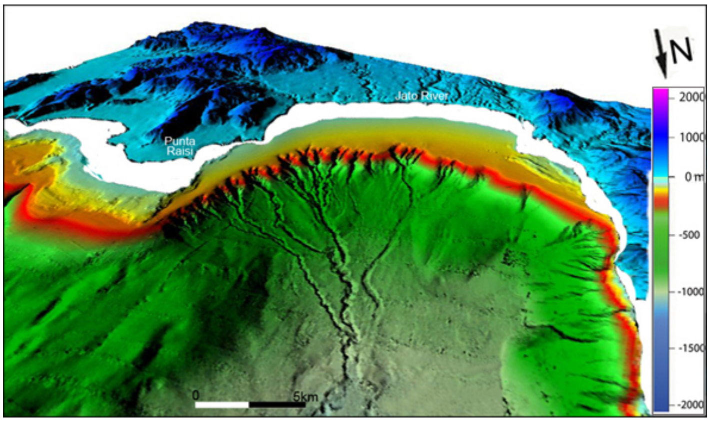

Fig. 5 - 3D shaded relief model (view from North-West) showing several gullies and canyon headscars indenting the shelf break along the southeastern sector of the Gulf of Castellammare.

The shelf break lies at depth of 130-190 m and shows a scalloped shape in the southeastern sector because of several gullies and canyon headscars indenting the shelf margin (Fig. 5). Out of the canyon headscars, the shelf break is a prograding, depositional straight feature. Along the San Vito peninsula the shelf break lies at depth of 60-100 m because of structural control and abundant retrogressive mass movement along the upper slope. In the small Bay of San Vito the continental shelf is very narrow and the shelf break lies at depth of 80-100 m reflecting a structural control.

5. SEISMOSTRATIGRAPHIC SETTING AND FEATURES

Along the study area the continental shelf is characterized by an extensive unconformity eroding a seaward dipping mixed (lithoclastic/bioclastic) Pleistocene succession. In the seismic reflection profiles these horizons can be assembled into packages of reflectors showing specific seismic attributes (seismostratigraphic units). As several Authors have documented along other Mediterranean margins (Chiocci et al., 1991; Correggiari et al., 1996; Hernandez-Molina et al., 1994; Tesson et al., 2000; Trincardi & Field, 1991 among others), the cyclic change of these attributes almost certainly is a response to subsequent sedimentary environment variations controlled by Quaternary eustatic sea-level fluctuations.

The unconformity is a subaerial erosional surface formed during the last eustatic sea level fall ended in the LGM (20-18 ka) and shaped again during the Late Quaternary-Holocene sea level rise that generated a "transgressive surface of erosion" (Nummedal & Swift, 1987). As consequence of this polygenic genesis, the unconformity is punctuated by incised valley, submerged cliff and isolated topographic relieves corresponding to outcrops of the rocky substrate, mud volcanoes, biogenic mounds.

This prominent unconformity is in turn the lower boundary of the sedimentary succession deposited during the last eustatic change (last 125 ky), which can be interpreted as a IV order depositional sequence (Late Quaternary Depositional Sequence, LQDS). In the LQDS we recognized four systems tracts, separated by basin-wide key surfaces identified by lateral terminations of reflectors, and deposited during specific segment of the last sea level change. The LQDS extends above the continental shelf and upper slope along the different sectors of the margin with considerably variable internal geometry and stratigraphic relationships with the underlying units.

5.1 Gulfs of Termini and Palermo

In these sectors the stratigraphic features of the LQDS and underlying Pleistocene succession are very uniform, so they will be illustrated together. We will describe the systems tracts from the older to the younger.

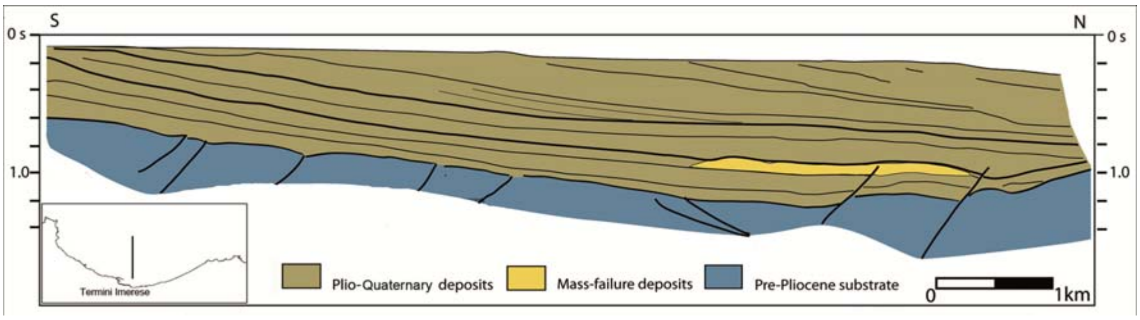

Fig. 6 - General stratigraphic pattern of Pleistocene seismic units buried beneath the continental shelf in the Gulf of Termini (as worked out from multi-channel seismic profiles.

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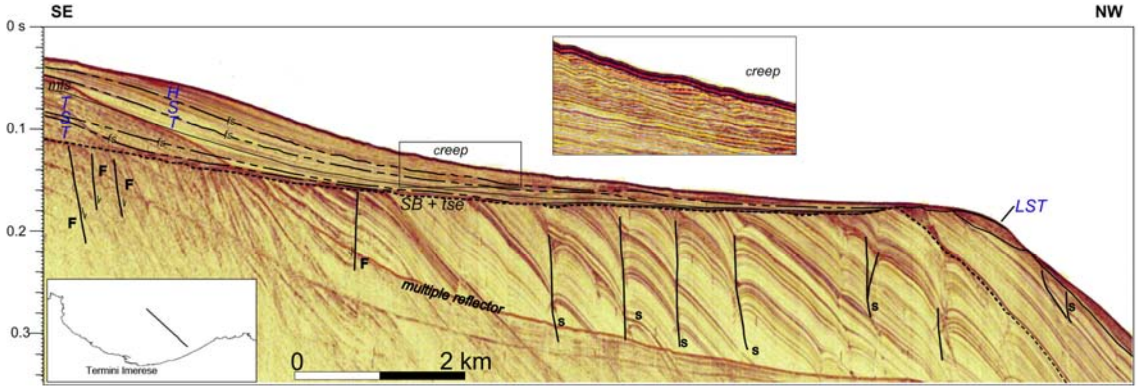

Fig. 7 - High resolution seismic profile (Sparker 1 kJ) showing the seismic units and facies interpreted in the Quaternary succession. Interbedded, progradational wedges (LST) are present along the outer shelf; SB: lower sequence boundary of the LQDS; F: fault; s: sliding plane (see text for more detail; modified from Pepe et al., 2003).

Deposits accumulated during the sea level fall form progradational sedimentary wedges perched along the shelf margin (Figs. 6-7). They are imaged by high resolution seismic profiles with reflection-free seismic pattern or thin, oblique tangential/parallel reflectors, 3.5° seaward sloping, locally involved in slumping. Wedges are up to 50 ms (t.w.t.) thick and up to 2 km wide; landward they onlap the late Pleistocene erosive unconformity at 110-130 m of water depth, about 15 km far from the present day coastline along the Gulf of Termini. We interpreted these wedges as forming the Falling stage systems tract (FSST).

Along the shelf edge progradational wedges showing oblique parallel horizons form the Lowstand systems tract (LST, Fig. 8). Seaward the wedges pinch-out at water depth of 150-190 m; the thickness is up to 100 ms (t.w.t.). These wedges formed during the LGM lowstand (20-18 ka) and are stacked with the FSST along the shelf margin. In plain view, FSST and LST wedges extend along the shelf margin for several km. They are absent only in the canyon headscars and, in the Gulf of Palermo, along a shelf break segment, about 5 km

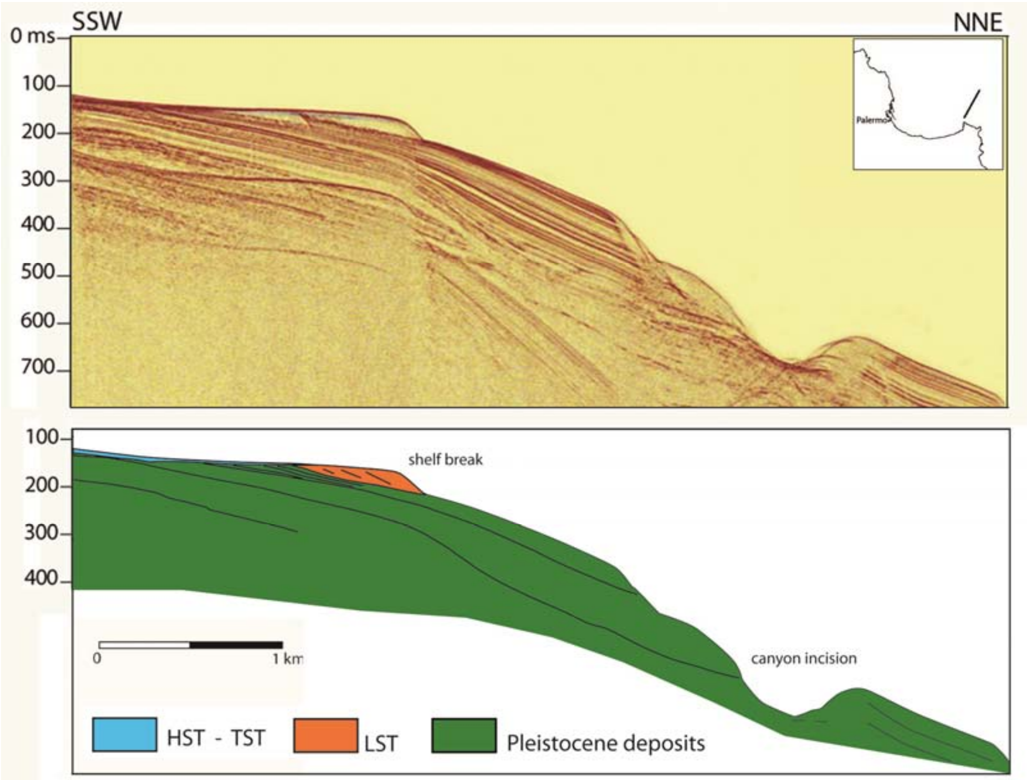

Fig. 8 - In the Palermo and Termini Gulfs, sedimentary progradational wedges along the shelf margin show reflection-free seismic facies or high frequency, low amplitude downlapping reflectors. Almost two progradational wedges are stacked along the shelf margin. Along the upper slope, Quaternary horizons are truncated by a canyon incision of a tributary of the Eleuterio canyon (Sparker 1 kJ seismic profile).

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long, between the Oreto and the Eleuterio canyon.

Samples coming from the upper portion of the prograding shelf margin wedges reveals coarse grained bioclastic sands containing benthic foraminifera deposited in a very shallow water environment during a cold period (Catalano et al., 2011b).

At the top both the FSST and the LST are truncated by the transgressive surface of erosion (t.s.e.) that downslope merge into a drowing surface (Fig. 8). Landward, in the inner shelf, this surface is scoured by a few incised valleys up to one hundred meters wide and ten meters deep.

Moving toward the inner shelf, a transgressive sedimentary wedge lies above the t.s.e.; the wedge displays even subparallel reflection configuration and thins seaward generating an apparent truncation in the seismic profiles. This wedge, interpreted as the Transgressive Systems Tract (TST) is very thin in the Gulf of Palermo (Fig. 8) and thicker in the Gulf of Termini Imerese (Fig. 7) where three backstepping parasequences can be recognized that are bounded by flooding surfaces. The lowermost parasequence lies above an extensive submerged wave cut terrace; the uppermost parasequence is thicker in the sector offshore the mouths of the Imera and Torto River.

A downlap surface (Fig. 7) marking the transition between TST and Highstand System Tracts (HST) seismic units, corresponds to the maximum flooding surface (*sensu* Vail, 1987). The overlying sedimentary wedge, interpreted as the HST, is formed by thin, continuous and aggrading horizons evolving upwards to slightly prograding reflectors. Landward this unit is continuous with the modern coastal sedimentary wedge. In front of the Imera River mouth the HST deposits appear involved in creeping interpreted as syn-sedimentary gravity features. In this sector the sea floor instability is promoted by high sedimentary supply, earthquakes, fluid seepage. Alternatively these structures were interpreted as due to waves, hyperpycnal flows and bottom currents (Urgeles et al., 2011).

As consequence of the wedge geometry, the HST thickness regularly increases landward up to 35 m in front of the main river mouths. At places seaward extension of this unit extends up to the shelf edge, completely burying the underlying TST unit.

The thickness of the TST and HST deposits rapidly varies along the margin resulting thicker in the central sector of the gulfs and in front of the entry points along the coast; otherwise, their thickness thins towards the gulf edges.

5.2. Offshore Palermo Salient

In this area, inner and outer continental shelf show very different setting. Along the inner shelf rocky substratum outcrops very extensively, truncated by an erosional surface; in the high resolution seismic profiles this surface is imaged as the reflective top of the acoustic basement. Along the outer shelf the sedimentary Quaternary succession is present, and in the upper part we recognized deposits pertaining to the LQDS (Fig. 9).

Along the shelf margin, FSST and LST deposits are stacked generating sedimentary prograding wedges

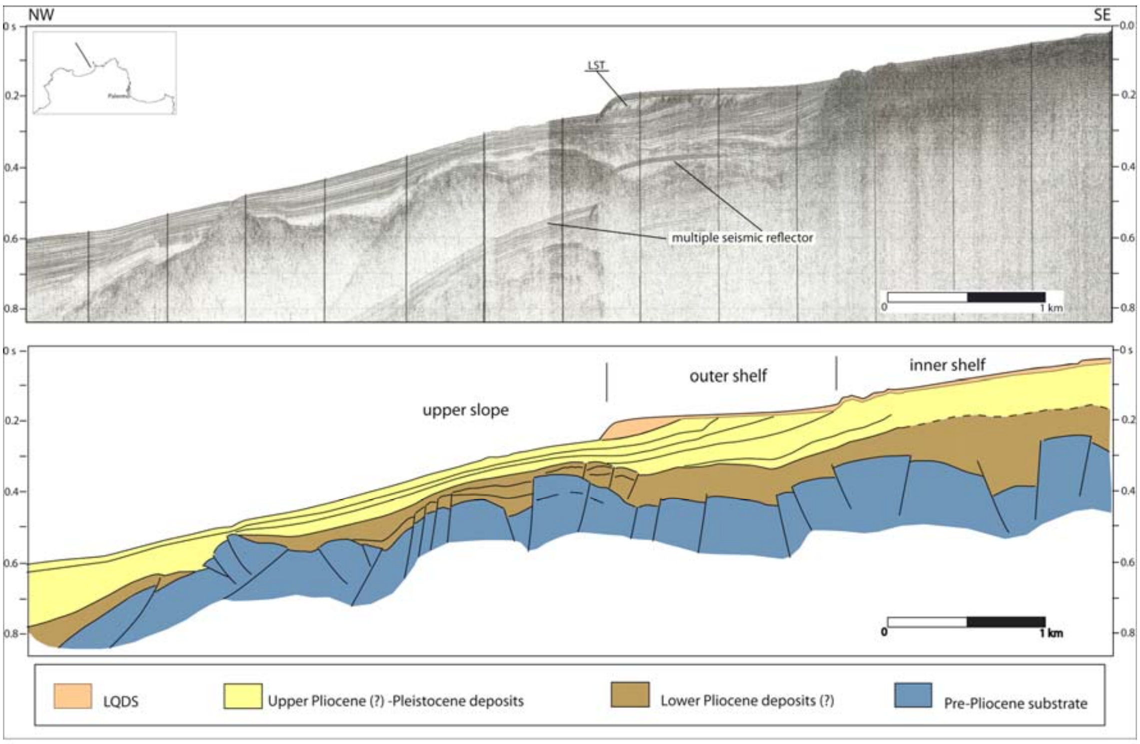

Fig. 9 - Seismic section crossing the Palermo Salient (offshore Bay of Carini). The seismic profile (Sparker 1 kJ) shows both the upper slope and the continental shelf where two distinct sectors can be separated; a prominent break-in-slope divides the two sectors. Along the outer shelf the sea floor is sub-horizontal, in the inner shelf it assumes an about 1.5° slope. According to our interpretation, the top of acoustic basement corresponds to the base of Plio-Pleistocene sequence. This horizon is affected by folding and reverse faults. Inside the Plio-Pleistocene sequence, a prominent unconformity separates two seismostratigraphic units. The lower one (Zanclean in age?) displays a predominant reflection-free seismic facies and appears deformed.

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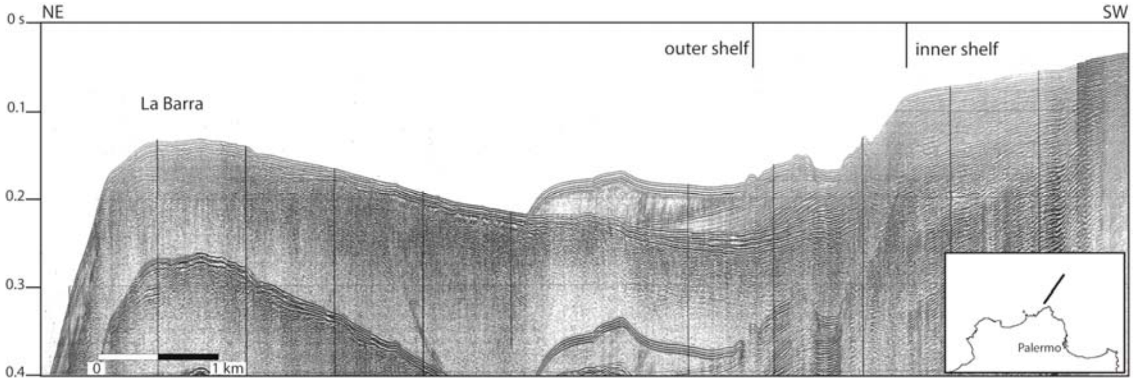

Fig. 10 - Seismic reflection profile (Sparker 1 kJ) at the north-east end of the Palermo salient. Here the continental shelf widens to 8.5 km and displays a very irregular morphology characterized by an inner and an outer sectors separated by a prominent break-in-slope partly buried beneath a stack of prograding sedimentary wedges. These downlapping, regressive deposits does not extend to the shelf margin where a landward sloping abrasion surface outcrops at the sea bed.

with thin, oblique parallel or tangential downlapping reflectors; reflection-free seismic configuration is also present (Fig. 9). Prograding wedges extend downslope up to more than 200 m water depth and landward onlap the Pleistocene succession at water depth of 110-120. Upwards, prograding reflector show lateral termination of toplap or erosional truncation. Along the shelf edge the prograding wedge is almost continuous for about 15 km displaying a maximum extension of 2 km and a thickness up to 30 m.

The shelf edge is depositional and corresponds to the offlap break of the outermost prograding wedge, except around La Barra (Fig. 10) where a deeper, erosive, structural shelf break is also present seaward of the depositional one (Agate et al., 2004).

Along the inner shelf FSST and LST deposits are absent. In this sector TST and HST units are very thin, often thinner than seismic resolution but they have been documented by samples (Ferretti et al., 1994).

5.3. Gulf of Castellammare

Except the San Vito peninsula offshore, the continental shelf of the Castellammare Gulf is the result of the Quaternary progradation of a clastic sedimentary succession truncated by the erosional surface formed during the last glacioeustatic fluctuation.

Above this unconformity the deposits pertaining to the LQDS can be subdivided into four units (Fig. 11), showing different sedimentary and seismostratigraphic expression in each sectors of the basin. The lower boundary is represented on the continental shelf by an unconformity surface of subaerial exposure and fluvial down-cut, and a correlative paraconformity on the upper slope, characterised by the occurrence of multiple linked scars. On the shelf, at 70-90 m below the sea level, the lower boundary is a polygenic regressive surface of erosion, extending landwards to a subaerial unconformity, and seawards to a marine erosional surface. Morphological steps and terrace-like features characterize the SDTQ lower boundary, cut through by a sharp network of incisions (Fig. 11), connecting the mainland incised valleys to the main submarine canyons.

The FSST has been identified in the outer shelf (Fig. 11), where it onlaps the LQDS lower boundary, at an average distance of 9 km from the present shoreline, and at depths of 110-120 m. The prevalent seismic facies is characterised by complex sigmoid-oblique reflectors and in rare cases oblique-parallel. Reflectors show medium amplitudes and are interrupted by rotational faults or affected by slope failures (Fig. 11). The amplitude and the lateral continuity of seismic horizons decrease seawards.

A shelf margin wedge forming the LST (Fig. 11) is situated in the eastern and central sector of the gulf, near the present-day shelf edge, and in the upper slope. It shows predominantly oblique, medium and high amplitude reflectors of good lateral continuity, with foresets gradients ranging from 4° to 10°. Seawards, reflectors become parallel to the downlap surface and merge into the high amplitude and laterally continuous upper slope reflectors. At the base of these shelf-perched units, chaotic seismic facies and small superimposed mounds have been identified in close association to gullies and canyons, cutting the outer shelf.

The depocenters of FSST and LST lengthen parallel to the paleomargin of the continental shelf in an E-W direction but the greatest thickness, exceeding 40 ms (t.w.t.), is identified near to the canyon heads.

The top of the shelf margin units is a transgression erosional surface (*ravinement surface*, Fig. 11); Nummedal & Swift, 1987) replaced in the upper slope by a drowning surface, without erosional features.

The TST (Fig. 11) is bounded at the base by an irregular transgressive erosional surface, with wave-cut terraces and channel features, reaching 500 m in width and 10 m in depth. The most striking feature is the retrogradational pattern of three parasequences separated by mixed (flooding and erosional) surfaces, extending laterally throughout the area (Agate et al., 2005). The three sub-units display a progressive landward shift of the coastal onlaps, which encroach between 98 m to 90 m, 75 m to 63 m, and 60 m to 45 m water depths.

The downlap surface at the transition between TST and HST corresponds to the maximum flooding surface (*sensu* Vail, 1987). It correlates with a very wide and strongly reflective horizon on the slope, the seismic expression of the condensed section (*sensu* Loutit et al., 1988). In the inner shelf between the mouth of the Nocella River and the overhanging coast of Capo Rama and off the Freddo and Jato Rivers, acoustic masking affects this surface (Fig. 11) suggesting the presence of biogenic gas. The upper stratigraphic limit of the HST is represented by the present day depositional surface (sea bottom). The HST is marked by a thick prograding wedge, which extends continuously from the inner as

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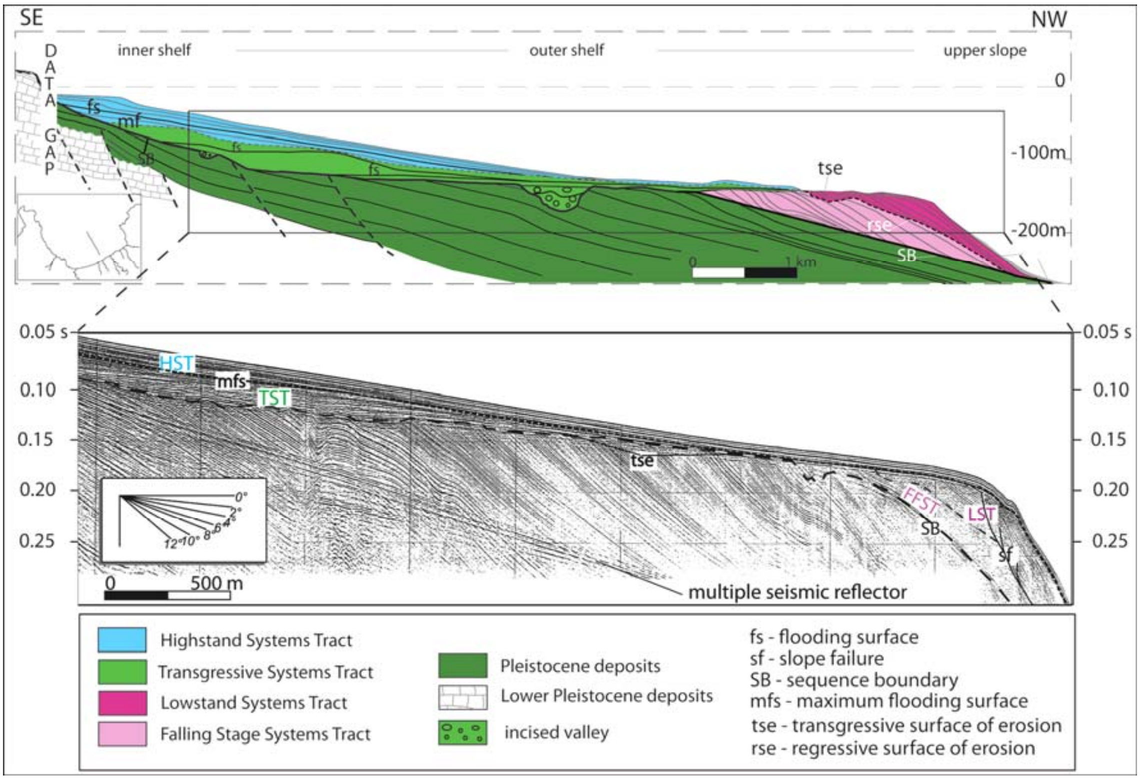

Fig. 11 - Seismic reflection profile (below; Sparker 1 kJ) and stratigraphic interpretation of the middle (?)-late Quaternary sedimentary succession buried beneath the continental shelf in the Gulf of Castellammare. The interpretative model images also a possible correlation to the deposits outcropping along the coastal zone (see text for more detail; modified from Agate et al., 2005).

far as the middle-outer shelf (Fig. 11). Analysis of the high-resolution seismic profiles has enabled the subdivision of HST into two parasequences, separated by an erosional surface. The lower parasequence shows faintly prograding geometries, shingled and oblique parallel, while the upper is oblique tangential. The modern depositional surface truncates the topsets of the last parasequence, suggesting the position of the modern fair-weather base level at 20 m of depth.

In the dip sections, the predominant seismic facies is oblique-sigmoid, with high amplitude and good laterally continuous reflectors, which merge seawards with a slope of approximately 1,5°. In the strike sections, seismic profiles show lateral variations of the facies: lobed facies with internal configurations of the hummocky type overlap with tabular facies faintly clinostratified dipping towards the southwest.

In the inner shelf, opposite the Freddo and the Jato Rivers, HST is deformed by upslope migrating wave structures (Fig. 15 in Agate et al., 2005), related to the acoustically transparent lenticular bodies, with an erosive base. These morphologies lie at 2-3 km seaward the mouths of the Freddo and the Jato Rivers, within a band trending W-E in subsurface depths from 75 to 25 ms (t.w.t.), where the thickness of the HST exceeds 25 m close to the river mouths. Pockmarks in the subsurface occur up-dip the most significant wipe-out zones and they point out the existence of gas-charged fluid expulsion.

The TST has four depocenters, aligned parallel to the shoreline off major river mouths, as in the central gulf, or at the base of the steep paleocliff in the eastern gulf off Capo Rama. Close to the western edge of the Castellammare Gulf the continental shelf is narrower and the seabed is a marine transgressive surface cut above the pre-Quaternary rocky substrate, at places floored by a very thin, shallow sedimentary cover.

5.4. Structural features

During the Pleistocene, faults, as well as folded structures, exerted a control on the morphology of the present day coastal areas and shelf-slope system, as for the submarine canyons and the mass failure processes.

In the Termini Gulf E-W to NE-SW-trending normal faults are prevailing. Very recent NW-SE vertical faults displace the buried Quaternary succession in the western sector, being also seismically active.

In the Palermo Gulf NNW-SSE fault systems, with a downthrow ranging from some tens to 150 m, are prevalent off Monte Pellegrino and in the southeastern side (off the head of the Eleuterio canyon), whilst to the north, between Capo Gallo and La Barra, faults appear to have a dominant NNE-SSW trend. Pockmarks and mounds are often aligned with the fault systems trends.

In the Monti di Palermo offshore main fault systems are and near vertical, oriented ENE-WSW (see La Barra structural high) or NNW-SSE, dipping NNEward. WNW-ESE trending fault systems were recognized parallel to the coastline. In the Carini Bay, inner continental shelf is characterized by N-S and NNE-SSW fault systems with variable downthrow.

In the Gulf of Castellammare the continental shelf develops in the southern part of a tectonic depression that formed during the Quaternary (Fig. 11). It is bounded to the East by N-S to NNW-SSE, with some hundreds of meters of downthrow, along which Meso-Cenozoic carbonate succession is juxtaposed to Plio-Quatermary deposits; to the South pre-Pliocene deposits are intensely folded and dissected by both reverse and extensional N-S to NNW-SSE faults, even very recent; to the West by NNE-SSW, NS and NNW-SSE faults.

6. DISCUSSION

Several evidences highlight that the North Sicily continental margin is tectonically immature. The Plio-Quaternary tectonic evolution of the NW Sicily margin produced the development of a morphostructural setting characterized by a series of depressions (intraslope basins) separated by structural highs along the margin (Agate et al., 1993), as result of differential uplift and subsidence during Neogene to Recent times.

Recent tectonic activity is testified by neotectonic elements and seismic activity (Fig. 1), calculated uplift rates, depositional alternating with structural edge, present lack of highstand-transgressive systems tracts in the oldest depositional sequences recognized along the margin.

Furthermore, the occurrence of pockmarks and mounds probably consisting of authigenic carbonates above faulted and folded strata suggests a local relationship between structural control and fluid escape. Some of the tectonic features could have represented a preferential escape route for fluids as evidenced by the pockmarks. Pockmarks may in turn trigger mass failures as evidenced by the headscarps observed below them (Lo Iacono et al., 2011). The structural features are possibly associated with the recent tectonics mapped on land (Catalano et al., 2011 a, b) as well as the widespread seismicity of the margin.

As a matter of fact tectonic activity persists today with the occurrence of shallow (<25 km) seismic events of low to moderate magnitude along an E-W trending belt located along the continental slope. The focal mechanisms related to the main seismic shocks are in agreement with a dominant NE-SW fault trend coupled with a NW-SE compressive offset direction. A minor cluster in the Monti di Palermo offshore well match with the extensional ENE-WSW trending extensional faults.

Uplift of the northern Sicily shelf and surrounding areas during the Pleistocene is testified also by the Pleistocene regressive coastal deposits in the western sector of the margin (Mauz et al., 1997; Arces et al., 2000), and the Pleistocene deposits, outcropping close to the study area, which are uplifted tens of metres (Hugonie, 1982). Moreover, uplift of the continental margin, as a consequence of thermal perturbation due to the thinning of the lithosphere which is not compensated by local isostasy, is predicted by forward modeling (Pepe et al., 2003), thus constraining the late Neogene to Recent tectonic and stratigraphic evolution of the margin.

Therefore, it is evident that along the North Sicily continental margin eustatic and tectonic processes combine to cause both relatively short- and long-term sea-level changes which control the space available for sediments, forming a number of depositional sequences from the early (?) Pleistocene to the Holocene.

6.1. Effects of eustatic sea-level changes

Subsequent, rapid sea level changes impacted the continental margins as consequence of astronomically forced, worldwide climatic changes occurred during Quaternary age. As documented by several studies on Oxigen isotopes (Chappel & Schackleton, 1986; Imbrie et al., 1984; Williams et al., 1988), middle-late Quaternary sea-level changes have been asymmetrical fluctuations characterized by slow falling stages (1 mm/y) followed by fast rising stage (1 cm/y); average amplitude of cycles was 100-150 m and the period was about 100-200 ky. As we have illustrated, the internal geometry of the LQDS well documents the sedimentary response to specific segments of the last glacio-eustatic fluctuation.

The effects of eustatic changes appear less evident in the more ancient deposits where complete depositional sequences have not been detected. According to us, the interpreted seismic profiles does not image past shelfal TST and/or HST deposits and subsequent erosional surfaces are not clearly distinguishable. Otherwise, beneath the LQDS, oblique seawards dipping layers only are preserved with small, interbedded, prograding wedges. We hypothesize these deposits recorded falling and lowstand depositional stages respectively (Caruso et al., 2011).

A possible explanation for this could be the tectonic evolution of the margin. According to Mougenot et al., (1983), in a prograding type shelf margin, the sedimentary response to sea-level fluctuations is better preserved for the influence of important subsidence. It does not seems the case of the NW Sicily offshore where high frequency sea-level changes punctuated a slow, long-lasting tectonic uplift.

Even if the effects of sea-level changes are ubiquitarious, thickness and internal geometry of LQDS are also controlled by margin physiography, sedimentary input and local hydrodynamic conditions. TST and HST deposits are thicker and extensive in the central sectors of gulfs where a major number of sedimentary entry points are present. This aspect contributes to differentiate the morpho-stratigraphic pattern of *depositional shelves*, where TST and HST deposits are extensive and well developed, from *structural-erosive* ones where TST and HST deposits are absent or very condensed (Fig. 12).

6.2. Different types of continental shelf

In physiographic setting as that bordering majority of the Tyrrhenian Sea, mainly characterized by a well-defined continental shelf-slope system associated to a pronounced shelf break, during the Late Quaternary sea level changes type 1 depositional sequences (Vail, 1987) developed, characterized by enhanced lower sequence boundary. However, even if glacio-eustacy is an ubiquitarious process, different types of depositional settings are distinguished in the shelfal sectors, mainly depending on subsidence, local climatic conditions and total sediment supply; moreover, localized features occur due to continental shelf palaeo-topography and distribution of entry points along the migrating shoreline. In fact, all these factors determine both location and depth of sedimentary deposits generated during the eustatic cycle.

In the investigated area the analysis of stratal pattern, lithological assemblages and architecture of depositional sequences, the identification of different stratigraphic and morphostructural settings along the margin, led to the recognition of two main types of continental shelf (Fig. 12), structural-erosive and depositional

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shelves respectively. For each of these types, interaction of tectonics, sea-level change and different types of sedimentary inputs developed different types of prograding shelf margin and different internal geometry of LQDS.

Type 1 are predominantly rocky shelves, where seabed corresponds to polygenic erosional surfaces modeled on a pre-Calabrian bedrock, in places covered by thin layers of Holocene deposits. This type is found in the structurally high areas in the Monti di Palermo offshore and around the main rocky headlands (Capo San Vito, Monte Catalfano). They can be divided into two subtypes (Fig. 12): 1A are rocky shelves accompanied by a moderate frontal sedimentary prism; 1B are rocky shelves with a structural edge (the sedimentary prism, although present, does not extend to the edge).

Type 2 are depositional shelves (prevalent or exclusive sedimentary origin), in which the pre-Calabrian bedrock is buried by a considerable thickness of Quaternary sediments and does not significantly influence the sea floor morphology; seaward progradational outbuilding contributes more than one half of the entire shelf width. Also in this case it is possible to distinguish two subtypes (Fig. 12): 2A are shelves in which the substrate deepen regularly seaward; 2B are shelves in which the structural setting determines a substrate uplift in correspondence of the current position of the shelf break (in this case the substrate is at shallow depths, providing a support for sedimentary prism accumulate and expand). The depositional shelves occur in the Castellammare, Palermo and Termini Imerese gulfs representing the 2A type, the type of continental shelf most widespread in the area. In this type of shelf we can find, in the inner platform, thick Holocene sedimentary wedges that are absent in the shelves of the first type.

When we compare stratigraphic architecture and depositional setting observed in the north-western Sicily offshore with other Tyrrhenian margins, there is a striking similarity mostly with the offshore Calabria and Campania. In these sectors we can observe depositional (type 2) shelves along the gulfs, e.g. Gulf of S. Eufemia (Chiocci et al., 1989) and Gulf of Salerno (Aucelli et al., 2012); otherwise, predominantly rocky shelves (type 1) are widespread in front of morpho-structural salient, e.g. Punta Licosa (Trincardi and Field, 1991; Ferraro et al., 1997) and Capo Suvero (Mongardi et al., 2004). This type (1) of continental shelf, characterized by prograding shelf margin deposits and absence of thick coastal prisms, is also common along linear margin (without coastal embayment) with scarce sedimentary supply, e.g. Marettimo Channel, in the Egadi islands area (D'Angelo et al., 2004), and Tuscan Islands (Roveri & Correggiari, 2004), or along epicontinental shelf separated by the mainland, e.g. Adventure Bank (Colantoni et al., 1985). A similar variability of continental shelves, as that we illustrated respect to the NW Sicily offshore, has been detected by Corradi et al., (1984), along the Ligurian Sea margin.

6.3. Geological evolution

The trend to tectonic uplift recorded along the margin, documented by already described stratigraphic relationships and in agreement with the outcrop altitudes of paleo-shorelines along the coast, seems to start with the Ionian (middle Pleistocene). Previously,

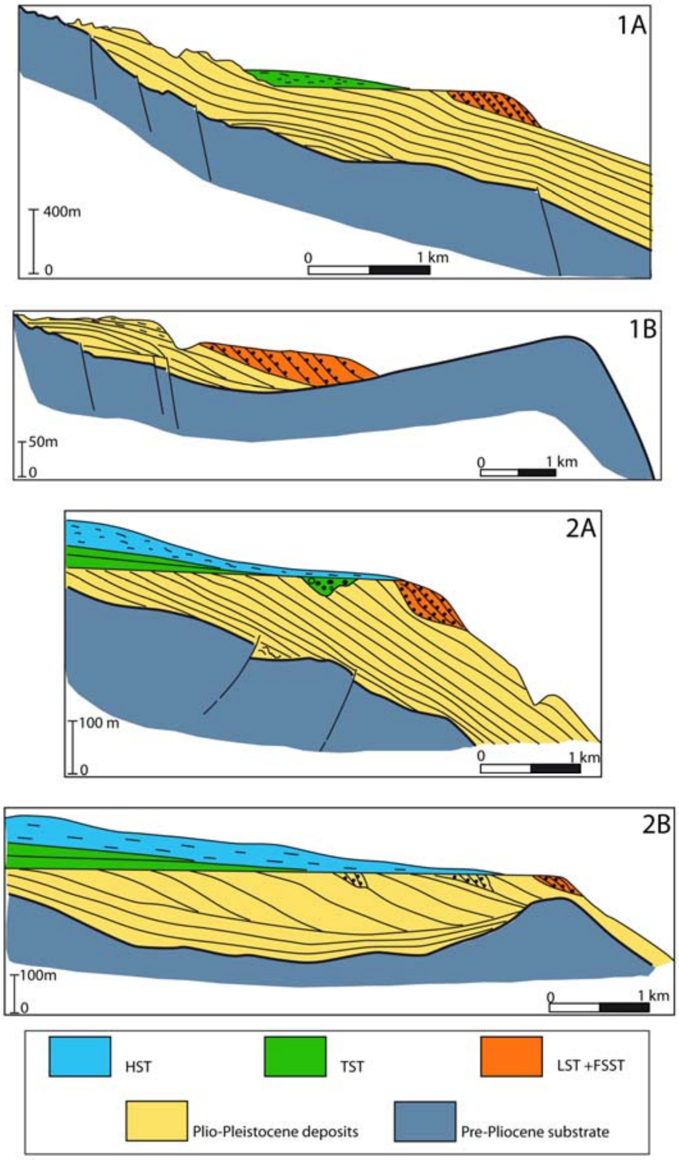

Fig. 12 - Cartoons image the stratigraphic setting of the middle (?)-late Quaternary depositional units detected by means of seismostratigraphic analysis in different sectors of north-western Sicily continental shelf: 1A) Bay of Carini; 1B) La Barra salient; 2A) Gulf of Palermo and Gulf of Castellammare; 2B) Gulf of Termini Imerese. Quaternary deposits. The illustrated different settings are controlled by geological processes discussed in the text.

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the sea recorded an episode of deepening that has allowed transgression during the Calabrian in a large area of the north-western Sicily, where now a neritic succession some tens of meters thick outcrops, discordant on a pre Calabrian tightly deformed substrate (Ruggeri, 1978). The deposition of this succession marks the beginning of the formation of the continental shelf in northwestern Sicily margin, which, by the end of the Calabrian, under the influence of glacioeustatic fluctuations and slow uplift, produced a frontal accretion of the margin of some km (<10 km).

The recorded deepening of the margin at the beginning of the Calabrian and the subsequent uplift, which produced the emersion of the Calabrian portion of the continental shelf, now outcropping up to about 100 m a.s.l., may be related to the succession of compressional and extensional tectonic events recorded in the margin during the Plio-Quaternary.

7. CONCLUSIONS

The integrated analysis of morphobathymetric and high resolution seismic data collected on the continental shelf to slope system was used to illustrate the present stratigraphic and morphostructural setting of the North Sicily continental margin and its Late Neogene-Quaternary geological evolution.

We recognized an upper Pleistocene-Holocene sedimentary succession, deposited during the last eustatic change (last 125 ky). This succession, interpreted as a IV order depositional sequence (LQDS), show along the different sectors of the margin considerably variable internal geometry and different stratigraphic relationships with the underlying units. The lower boundary of the LQDS is represented by a subaerial erosional surface formed during the last eustatic sea level fall, ended in the LGM (20-18 ka), and shaped again during the Late Quaternary-Holocene sea level rise. This unconformity lies at the top of a seaward dipping Pleistocene succession whose depositional architecture is in turn controlled by Quaternary eustatic sea-level fluctuations.

Even if depositional sequences in this margin are the result of the interaction between sea level changes and sedimentation, the tectonic activity has played a key role, not only to determine the different characters of each sequence in different areas, but also in the creation of different types of continental shelves. As a consequence we recognize different types of continental shelf with different stratigraphic and morphostructural settings, identified on the basis of the occurrence and thickness of the LQDS deposits: a) type 1, predominantly rocky shelves, both accompanied by a moderate frontal sedimentary prism (1A) and with a structural edge (1B), in the structural highs of the Monti di Palermo offshore and around the main rocky headlands (Capo San Vito, Monte Catalfano); b) type 2, depositional shelves, in the Castellammare, Palermo and Termini Imerese gulfs, with a regular seaward deepening of the substrate (2A) and with a substrate uplift at the shelf break (2B).

A general tectonic uplift during the Pleistocene, together with the episodic alternation of extensional and compressional events, often with strike-slip component, is responsible for the thickness and facies variation and geomorphological features, both onland, where residual Pleistocene marine deposits today outcrops, and in the continental shelf, where most of the depositional sequences developed and are now recognized.

As well tectonic activity exerted a control on the geomorphological features of the present day coastal areas and shelf-slope system (e.g. pockmarks and mounds) as well as for the submarine canyons and the mass failure processes.

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